Labrador Sea Boundary Current and Convection Dynamics

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LONG-TERM GOALS

Our aim is to understand the physics of high-latitude convection, eddies, air-sea interaction and circulation, using direct observations made as part of the ONR Deep Convection ARI, and subsequently in collaborative surveys with Canadian oceanographers. Outside of the scope of this funded proposal, laboratory and numerical simulations and new observations are keys to understanding the dynamics of the high-latitude oceans. The key issues involve the cold-wind forced wintertime breakdown of the upper ocean stratification, convection to great depth, and the spawning of mesoscale eddies. At the larger scale these flows interact with boundary currents and continental shelf regions. We also are active in planning future strategies for exploring the high latitude oceans. Another long-range goal is the improvement of numerical ocean models and coupled ocean/atmosphere models, which are becoming the 'center-piece' of our science.

OBJECTIVES

The specific questions currently under study are: what is the source of the mesoscale eddies which populate the Labrador Sea? Why are those seen at our Bravo mooring dominantly anticyclones? Why did the weakening of cold-winter forcing of the Sea cause the dominant eddy energy to rise, and the eddies to be warm-core rather than cold-core? How does the annual cycle of heat storage and fresh-water storage in the Labrador Sea compare with the atmospheric forcing inferred from atmospheric centers' (NCEP and ECMWF) data? Is the oceanic water column in fact a better index of atmosphere-ocean heat flux than are the weather models? How does the Sea respond when atmospheric forcing is switched off for several years? Can we describe in detail the interaction of the 500 km wide Labrador Sea Water gyre with its encircling boundary currents; what is the out-mixing rate for Labrador Sea Water, which communicates with the surrounding ocean? How can a more systematic, 3-dimensional data set be accumulated in the future?

APPROACH

The data sets we are analyzing include 6 years of mooring data, predominantly that of the Bravo mooring supported under NOAA funding, supplemented with ONR support; hydrography from the Hudson section between Hamilton Bank, Labrador and Cape Desolation, Greenland, most years in the 1990s, and special, 3-dimensional hydrographic programs involving the PI and BIO, October 1996 and May 1997. In addition, ONR funded moorings on the Labrador continental slope are yielding valuable data about the strong boundary current circulation, which catches the dominant Denmark Strait Overflow water and other water masses that feed the global circulation. Finally, we are planning strategies to use the Eriksen Seaglider to make dense, interactive, 3-dimensional observations of temperature, salinity, dissolved oxygen, chlorophyll and nitrate with cost efficiency that is orders of magnitude better than currently possible.

WORK COMPLETED

Jonathan Lilly, graduate research assistant under this grant, has combined Topex-Poseidon and ERS altimetry with our hydrography and mooring data, to describe the annual cycle of eddy energy in the Labrador Sea. We have also done a detailed study of restratification of the Sea after winter is over, when the water column relaxes back toward the warm, saline properties of the surrounding ocean. This restratification also continues over longer time-scale, during years when winters are warm and mild. The portrait of the water column from 1990 to 2000 is a striking example of massive interannual variability of convection depth, eddy energy, and circulation. On the planning side, we submitted a proposal to ONR to fund Seagliders in the Labrador Sea.

RESULTS

The origin of mesoscale eddies has been somewhat of a mystery (Figure 1). We know from lab and numerical models that wintertime cooling of a patch of ocean will quickly generate 100m to 500m wide plumes and, at the 'edges' of the cold forcing region, 10 km to 100 km mesoscale eddies. Boundary current instabilities are also very active in the Labrador Sea, and maps of eddy kinetic energy from altimetry show a maximum near the west coast of Greenland. The boundary currents flow counterclockwise round the Sea, separating from Greenland and flowing in deep water southwest to the Labrador continental shelf. At the separation point from Greenland, direct AVHRR temperature images and altimetry both show intense eddy activity. SAR images also show dipole eddy pairs shooting off the Labrador boundary current at Hamilton Bank.

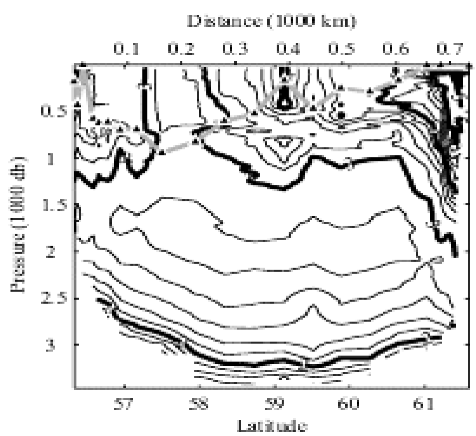

Figure 1. Winter 1998 section across Labrador Sea showing potential temperature contours. On the southwest side of the Sea, near Labrador, winter convection has reached ~600m depth, while on the northeast side near Greenland, warm intrusions are seen. Warm 'Irminger Water' eddies are later seen reaching the Bravo mooring. This section illustrates the two dominant sources of eddies: deep convection and boundary current instability. Section data courtesy of E. d'Asaro.

There is, most years, a late-winter maximum of eddy energy at Bravo, and Jonathan Lilly, graduate student under this grant, has followed its progression in space and time. The warm, saline eddies that dominate the Sea in mild winters are made of boundary current (Irminger-) water (see Figure 2). In cold winters these are destroyed by deep convection. Topex-Poseidon and ERS-1 altimetry has made it possible to map the larger-diameter eddies and their seasonal cycle (the altimeters miss the smaller cold-core eddies in Figure 2, left). There is a systematic movement of eddy activity from the Greenland coast southward across the Labrador Sea. The elusive life cycle of subpolar eddies seems now to be in our grasp; Lilly *et al.* 2000.

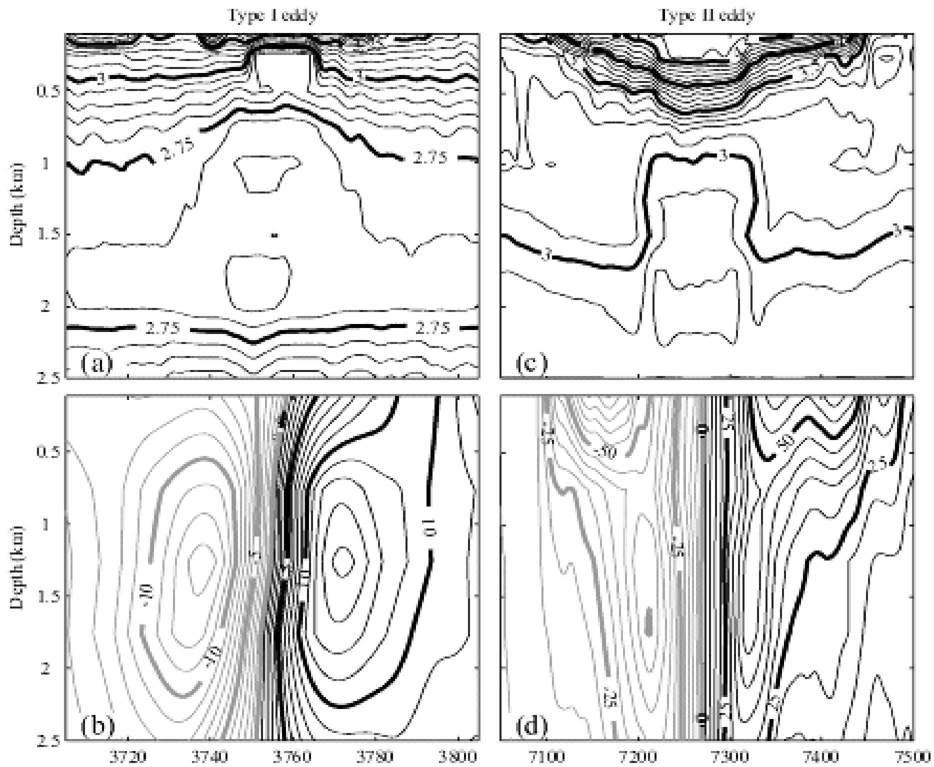

Figure 2. Cross-sections of two dominant mesoscale eddy types in the Labrador Sea, seen passing the Bravo mooring. Left: cold eddies encapsulating deeply convected water after winter, about 20 km in diameter. Right: warm eddies originating in boundary current encircling the Sea, about 50 km in diameter. Both types are dominated by anticyclones at site Bravo. Upper: potential temperature. Lower: azimuthal velocity.

Restratification of the water column after deep convection, in spring and summer, and during years of tepid atmospheric forcing, is perhaps a second compelling question about the subpolar oceans. It is clear that the in-mixing of the upper, low-salinity, cold waters is much more rapid than the in-mixing of deeper warm, high-salinity waters from the boundary current. PALACE float tracks have shown entry and exit from both northern and southern sides of the gyre. We have used CSS Hudson hydrographic cruises from May and October 1996 and May 1997 to evaluate the invasion of water from the boundary currents, after convection has wiped the slate clean. The renewal time of the upper waters is indeed less than one year, and that of the deeper waters is several years. An independent check of these results is in the 5-year relaxation of the Labrador Sea Water from 1996 to present, when winter forcing has been weak.

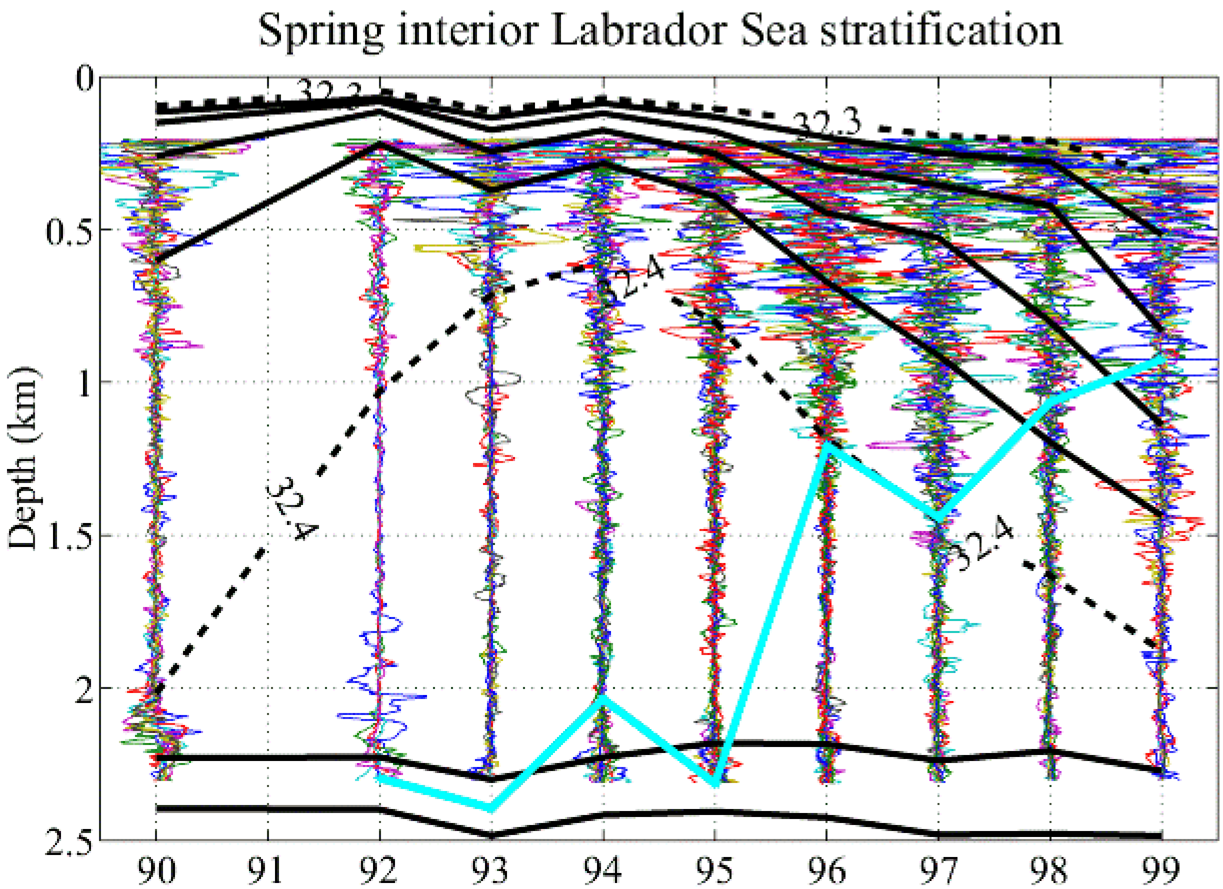

Figure 3. The springtime water column in the central Labrador Sea, from 1990 to 1999. Contours of potential density (bold, dark) show intensely mixed, deep convection of early 1990s relax in warmer winters after 1995. The base of the convective layer (bold,light) rises with time, and the fine-scale salinity features (wiggly curves) increase in strength as restratification develops.

Our boundary current moorings have provided a detailed portrait, for the first time, of the stack of water masses that circulate at speeds of 20 to 30 cm sec^{-1} round the rim of the Sea. The German group from Kiel, also working in the area, estimates mean transport in this system of about 40 x 10^{6} m^{3}sec^{-1}, which is impressively large. A very strong oscillation of the currents with period about 6 days is seen, and it is great enough to alias any transport measurement attempted from an individual ctd/adcp ship section. This illustrates the value of time-series moorings. The vertical structure of the boundary currents is strongly barotropic: the vertical shear is a small correction to this big, depth-independent flow. This again illustrates the impossibility of reconstructing the circulation from hydrographic data alone.

There is continuing work on the basic physics of convection (Boubnov and Rhines, 2000; Lazier, Rhines and Pickart, 2000).

IMPACT/APPLICATIONS

The ONR-led ARI in the Labrador Sea was amplified by the participation of NOAA, Canadian Division of Fisheries and Oceans, and the German project, *Dynamik Thermohaliner*

Zirculationsschwankungen. The radically changing climate of the high latitude world urgently requires observational programs in this region, and the tools, techniques and background data for this globally important problem were established by the Labrador Sea program.

It is important also to measure the impact of this program on education and public outreach. We have built over the past few years an unusual combination of seagoing observations, numerical models and fluids lab experiments in support of the Labrador Sea Program. Students, from graduate school down to grade school, have enjoyed this three-fold science. This summer we had 4 undergraduate students and 3 graduate students working in the GFD lab (http://www.ocean.washington.edu/research/gfd/gfd/html). It has had a strong influence on laboratory demonstrations which we regularly carry out for the 1st year graduate classes, in term-long projects courses, and in demonstrations for visiting admirals, the Director of NSF, and various and sundry classes of school-children. In the past year we have produced laboratory experiments and dialogue for science programs on BBC-2 Television, Granada Television and the Discovery Channel ('The Big Chill' and 'Planet Storm', respectively). Carrying out physics experiments in the lab, exploring the actual oceans, and relating these to storms on Jupiter and Earth, is an unequaled combination.

The 5-week ONR-supported summer course/workshop *Coastal and Estuarine Geophysical Fluid Dynamics* described below, under Related Projects, might be thought a model for involving students more actively in the excitement of sampling the coastal ocean. We now have the new technologies to slice and analyze these complex 3-dimensional, time-dependent regions. Fast, small boats with adcp and miniature towed ctd sensors, Seagliders and profiling moorings finally are up to this challenge. If teaching-related agency support could emerge to develop this resource into a regular facility, it could have marked effect on both science and education. The summer course research teams produced 2 detailed poster presentations for AGU Ocean Sciences Meeting, San Antonio TX, Jan. 2000. (see Friday Harbor Laboratories GFD Group, 1999 and MacDonald *et al.* 1999).

RELATED PROJECTS

1 – We (C.Eriksen and the PI) have proposed to ONR the deployment Seagliders in the Labrador Sea. The glider has passed several important performance exercises and begun collecting long data series in coastal regions. The availability of the Globalstar satellite system, with data-communication footprint covering most of the Atlantic to 70^0N, makes the future deep-ocean deployment a possibility. Glider surveys of the subpolar oceans can be extremely efficient, in two modes. First, a single glider can execute a 2500km long section spanning the subpolar Atlantic at ~ 60^0N, shore to shore, three to four times per deployment (~ 1 year). This gives the heat content, fresh-water content, water-mass maps, eddies (temperature, salinity, oxygen and chlorophyll) at high resolution, including crudely the annual cycle. Second, the glider can zig-zag along the path of the intense boundary currents, profiling them with interactive communication, and including shallow water shelf connections. Ice-covered regions must at present be avoided, but crucial passages and sills can be visited in summer. Under ice deployment may be possible in the future.

2 – Jerome Cuny and the PI have analyze sea-surface drifters (Niiler program) in the Labrador Sea. Cuny, being a non-US citizen, is funded by NSF. There is much interaction with the current ONR work however. The drifters give us quantitative measures of the Lagrangian circulation at the surface, especially in the boundary currents. We have established two principal pathways for the circulation between Greenland and Labrador. Lagrangian statistics and eddy energy maps and mean flow maps have been created (Cuny *et al.* 2000).

3 – Leif Thomas, a student under NSF support, and the PI have been investigating the geophysical fluid dynamics (GFD) of stratified spin-up, say when wind and cooling are applied to the surface of a stratified ocean. The wind-only case is one of the most basic problems in GFD. With cooling, it becomes a problem of relevance to the Labrador Sea. In particular, our moorings in the boundary currents show surprisingly deep convection in winter, despite an buoyant cap of fresh water overlying the ocean there. Onshore Ekman transport can, in our simulations, redirect and focus deep convection, giving it a mechanical 'push'. The studies are also directed at coastal upwelling.

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